High-Performance Beam Stabilization for Next-Generation ArF Beam Delivery Systems

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ABSTRACT

With the advent of 193 nm systems processing 300 mm wafers, the production lithography cell is about to undergo a technology shift. The mechanism for delivering the beam from the light source to the illumination system, here referred to as a Beam Delivery Unit (BDU), must change to meet the challenges imposed by this shift. To support these changes, Cymer is developing a BDU that will guarantee a stable beam at the scanner entrance during exposure. The beam stabilization control system has been implemented in a test BDU. We shall present results from experiments that demonstrate our ability to significantly improve short and long term "Beam Stability".
Keywords: Beam Stabilization, Lithography, Beam Delivery

1. INTRODUCTION

We adopt the term "Beam Stability" as a measure of how well the beam exiting the BDU tracks a specified target in the scanner. Quantitatively, beam stability is measured by position and pointing angle errors from the target as viewed along the optical axis of the beam. Improvements in beam stability will enable implementation of longer BDUs, decrease downtime, and improve optical performance at the scanner entrance to the point where designers could consider reducing specifications in other areas of the system.

In current BDUs the exit beam's pointing and position vary significantly from pulse-to-pulse. There are factors that degrade beam stability over the short and long term. Over the long term drifts in the light source-BDU system can degrade beam stability to a point where re-alignment is required. Current BDUs contain static beam pointing correction systems that provide automated re-alignment for large drifts. These require the scanner system to be off-line and cannot operate on a pulse-to-pulse basis to reduce short-term errors.

Short-term errors are a convolution of light source beam pointing fluctuations and those due to optics in the BDU. These fluctuations impose challenges for delivering a stable beam to the scanner. As lithography tool footprints increase, more light sources will be located outside the cleanroom, increasing BDU length. Since the light source is a cause of pointing error, the magnitude of the position errors at the scanner entrance increases with the distance between the light source and scanner. Without correction, the pointing and position errors may exceed the tolerances of certain next-generation scanner illumination and projection optics designs. Alternatively, reducing them might allow scanner optics designers freedom to relax tolerances elsewhere [4].

We shall describe an active control system that tightly controls short-term pointing and position errors, and also eliminates the need to take the scanner down to re-align long-term drifts. The system is comprised of three elements. A metrology module measures the position and pointing errors at the scanner entrance for every pulse from the light source. Turning mirrors mounted on two-axis, dual-stage motors steer the beam to minimize the measured errors. The dual-stage is a fast, small stroke motor mounted on a slow, large stroke platform. The fast stage compensates for short-term errors, while the slow stage compensates for larger long-term drifts. Third, a high-speed controller running robust algorithms processes the sensor data to generate command signals for the motors.

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Error Type:	Source:	Cymer Solutions:
(1) Beam drift (2) Pointing Error (3) Position Error	• Light source • Attenuator • Mechanical vibrations induced by fab or scanner	**Active Beam Pointing and Position Control during exposure**
Beam Misalignment	• BDU component replacement • Light source module replacement	**Auto-Alignment System**

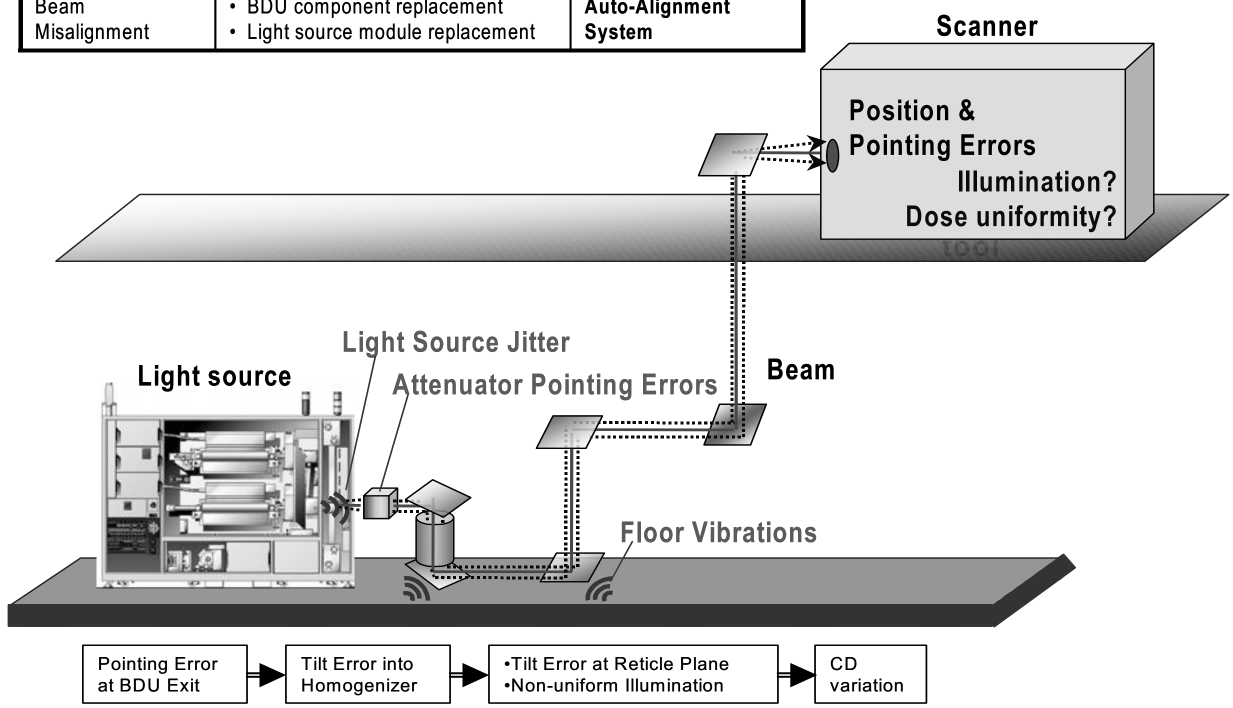
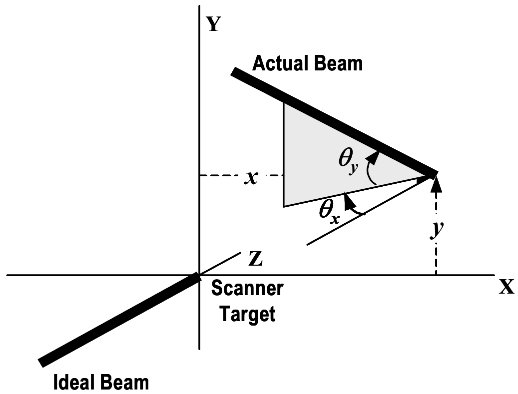


Figure 1: Beam stabilization errors are induced by jitter in beam from the light source and fab vibrations.

2. PROBLEM DEFINITION

The need for a BDU beam stabilization system is illustrated in Figure 1 where we show the primary components of a beam delivery system [1]. The beam leaving the light source must be projected many meters (2-20) and reflected off many turning mirrors as it travels from the light source to the scanner. The jitter in the beam exiting the laser for a typical light source operating in spec is on average 100um in position and 100urad in angle. The angular errors from the light source are preserved as the beam bounces off the turning mirrors. However vibrations from the fab environment will cause the mirrors to vibrate, and thus have the potential to increase the pointing errors. Regardless, for long BDUs, small pointing errors at the BDU entrance will lead to large position errors at the exit. In particular, a 100urad angular deviation over 20m would produce a 2mm shift in position. Optical attenuators needed to regulate dose levels are an additional sources of pointing errors.

Beam stabilization is concerned with the problem of using the turning mirrors in the BDU to steer the beam so that it tracks a specified target inside the scanner. The problem of steering a light beam to hit a target using mirrors is not new. There are many applications for continuous visible light, generated from HeNe lasers for example [2]. There are even implementations of beam steering for pulsed light sources [3]. We make an important distinction for our application. Namely, we seek to stabilize the beam in a pulse-to-pulse sense, and do so for ArF (193nm) pulsed light sources at rates up to 4kHz. For the BDU application, pulse-to-pulse correction enables improvements in the beam stability during wafer exposure. This is a key distinction and advantage over systems that can only correct for drifts via traditional beam steering while the system is off-line (not exposing wafers).



Errors	Description
x	Horizontal position error
y	Vertical position error
θ_x	Horizontal pointing error
θ_y	Vertical pointing error

Figure 2: Illustration of beam stabilization errors between an actual beam and an ideal beam that enters the target at the (X,Y,Z) origin along the Z axis.

There are four beam stabilization errors of interest, as illustrated in Figure 2. Performance is measured as a moving average since the scanner itself has an averaging effect on the beam. The window size for evaluating performance varies with the particular application. To evaluate the moving average, we assume the laser pulses occur in bursts, with constant repetition rate within each burst. Further, the moving average is calculated only within each burst (i.e., data from the end of one burst is not averaged with data from the beginning of the next). As an example, the moving average performance for horizontal position x for the k^{th} window in a burst of m pulses is

$$MA_x[k] = \frac{1}{n}\sum_{j=0}^{n-1} x[k-j], \quad k = n, n+1, \ldots m$$

Note that for each burst of m pulses, there are only m-n+1 windows in the burst. As a matter of choice, we ignore the incomplete windows up to pulse n in each burst, and only evaluate performance for the windows beyond pulse n.

3. TEST BDU SYSTEM DESCRIPTION

To validate our pulse-to-pulse beam stabilization technology in a realistic system, Cymer built a test BDU (Figure 3). Following the light path from the laser to the scanner, the key optical modules in the test BDU are: an attenuator, a turning mirror module, a beam expander, another turning mirror module, and finally a metrology module. The attenuator has been placed at the beginning of the BDU so that the beam stabilization system can compensate for any pointing errors it induces.

The turning mirror modules bend the beam 90 degrees. They can be placed in any orientation to bend the beam up, down, left and right. In the system shown, the first turning mirror bends the beam straight down toward the floor, and the second one bends the beam along the floor and to the right. Both turning mirror modules in the system shown contain a set of the staged beam stabilization actuators. Located after the first turning mirror is a 4-lens beam expander. By the appropriate selection of lenses, the beam expander can expand or contract the beam independently in the Horizontal (H) and Vertical (V) axes to deliver the desired beam size to the scanner entrance. The metrology module is located at the BDU exit and is designed to mount to the scanner. It contains the sensors and optical metrology used to generate the signals that drive the beam stabilization controller. In mounting to the scanner, the metrology module enables the stabilization system to deliver a stable beam at a scanner specified target in the scanner's reference frame. The metrology module also contains an energy sensor to monitor the beam energy entering the scanner. While the system shown in Figure 3 only contains two turning mirror modules, the Cymer BDU is a modular design that supports up to 5 turning mirrors. In addition, the modularity of the design enables many BDU configurations, including sub-fab configurations where the laser is located on a floor below the scanner possibly 20m away.

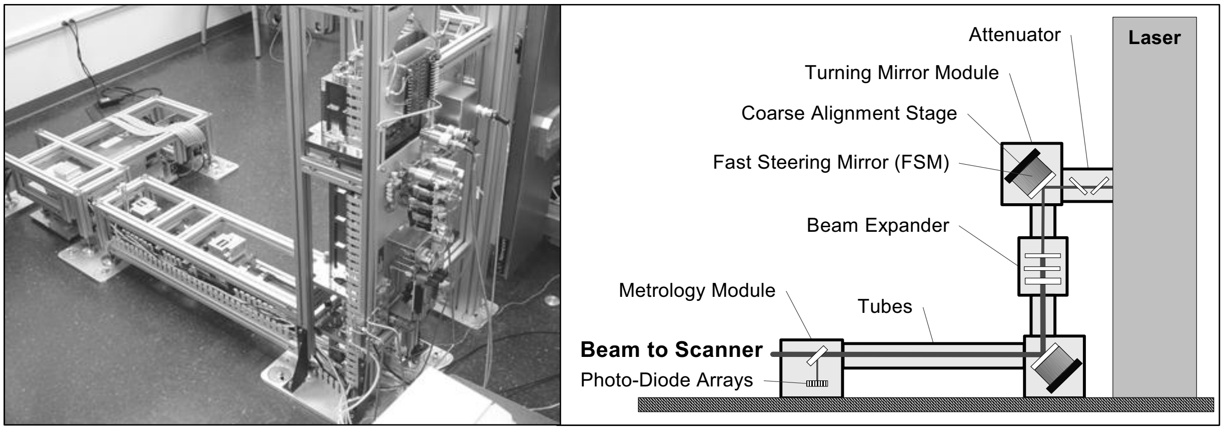


Figure 3: Cymer's Test Beam Delivery Unit.

4. BEAM STABILIZATION SYSTEM DESCRIPTION OVERVIEW

Cymer's system for implementing beam stabilization is illustrated in the block diagram in Figure 4. Photodiode Array (PDA) sensors in the metrology module sample the beam stabilization errors. PDA read out boards (PRBs) digitize the sensor signals and feed them to the controller. Algorithms in the controller process the sensor data and generate commands to move the turning mirrors. Each turning mirror has two axes, allowing us to independently control the four beam stabilization errors. Timing logic is required to run the PDA sensors. In particular, the system must know in advance when a pulse of light is coming. For the test system, we use the laser's internal metrology trigger as the input to the timing logic. In practice, the controller electronics are designed to work with the same pulse trigger provided to the laser by the scanner.

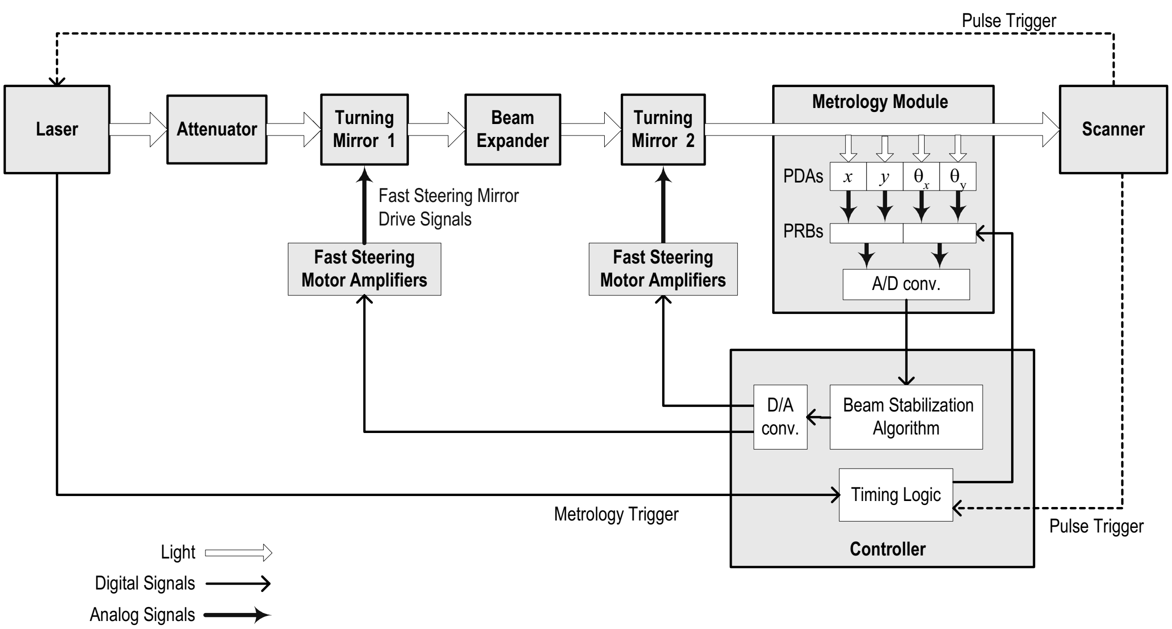


Figure 4: Block diagram of beam stabilization control system.

To achieve a beam stabilization system that operates pulse-to-pulse for ArF light sources we had to overcome three significant challenges. First, we had to develop a sensor system that was capable of measuring the beam stability errors for every pulse of light. Second, we had to develop a turning mirror actuator with a high natural resonant frequency to compensate for the fast pulse-to-pulse errors. Third, we needed an algorithm that was robust enough to run independent of the laser firing mode.

5. SENSOR METROLOGY

The sensor metrology module picks off a small fraction of the light exiting the BDU to sample the four beam stability errors for every pulse entering the scanner. Position errors are measured by placing a reduced image of the beam entering the sensor module onto photodiode array sensors. Shifts of the beam image correspond to shifts in the position of the beam as illustrated in Figure 5. Similarly, pointing errors are measured by placing the focal point of the beam onto PDA sensors. Shifts of the beam focal spot correspond to shifts in the beam angle. Within the metrology module, we use multiple wedges and reflections to simultaneously monitor the vertical and horizontal motions of the reduced beam image and focal spot. Figure 6 shows a sample of the images captured on the PDAs in the metrology module.

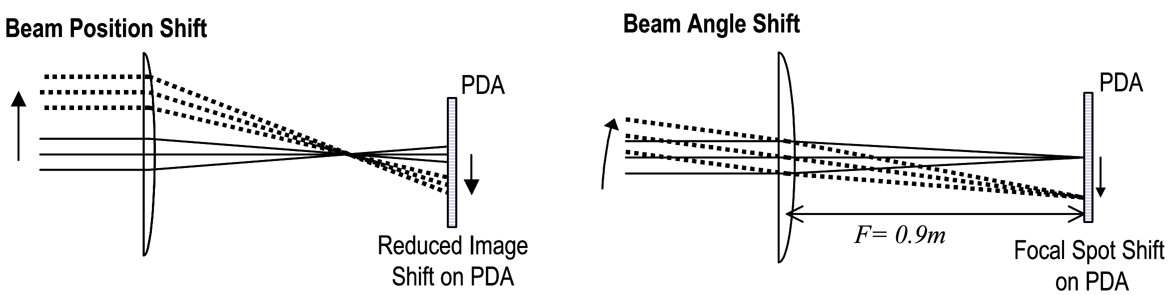


Figure 5: Shifts of beam image and focal spot on PDAs correspond to shifts of beam position and angle at scanner entrance.

While Photodiode arrays require sophisticated electronics and processing, they work reliably at 193nm and provide significantly higher resolution than other sensors (see Table 1).

Table 1: Benefits of photodiode arrays for beam stabilization.

Specification	Photodiode Array (PDA)	Quad Detectors
Performance at 193nm	***High***: Direct sampling of beam.	***Low:*** Cannot sample beam directly at 193nm. Requires fluorescing glass.
Resolution	***High***: 25-50um can be achieved by direct computation of spot locations.	***Low***: Spot location proportional to beam intensity. Susceptible to variations from hot spots in beam
Speed	***High***: Spots can be captured at rep rates exceeding 4kHz.	***Slow:*** Cannot discern variations from pulse-to-pulse at high rep rates.
Range	***Good:*** Appropriate optics and large active areas allow for large dynamic range.	***Good:*** Large active area allows for large dynamic range.
Linearity	***High***: Voltage/pixel is linear with intensity.	***Low:*** Output signals are not linear with spot displacement.
Electronics	***Complex:*** Must move and process hundreds of pixels of data per pulse	***Simple:*** Analog signal outputs, voltage proportional to displacement of spots.

To stabilize beam pointing and position errors, the raw PDA sensor data must be processed to determine the pointing and position errors from the scanner specified target. The technique employed is illustrated on the vertical position fringe in Figure 6. The scanner specified target corresponds to fixed locations on all 4 PDAs. If the center of all

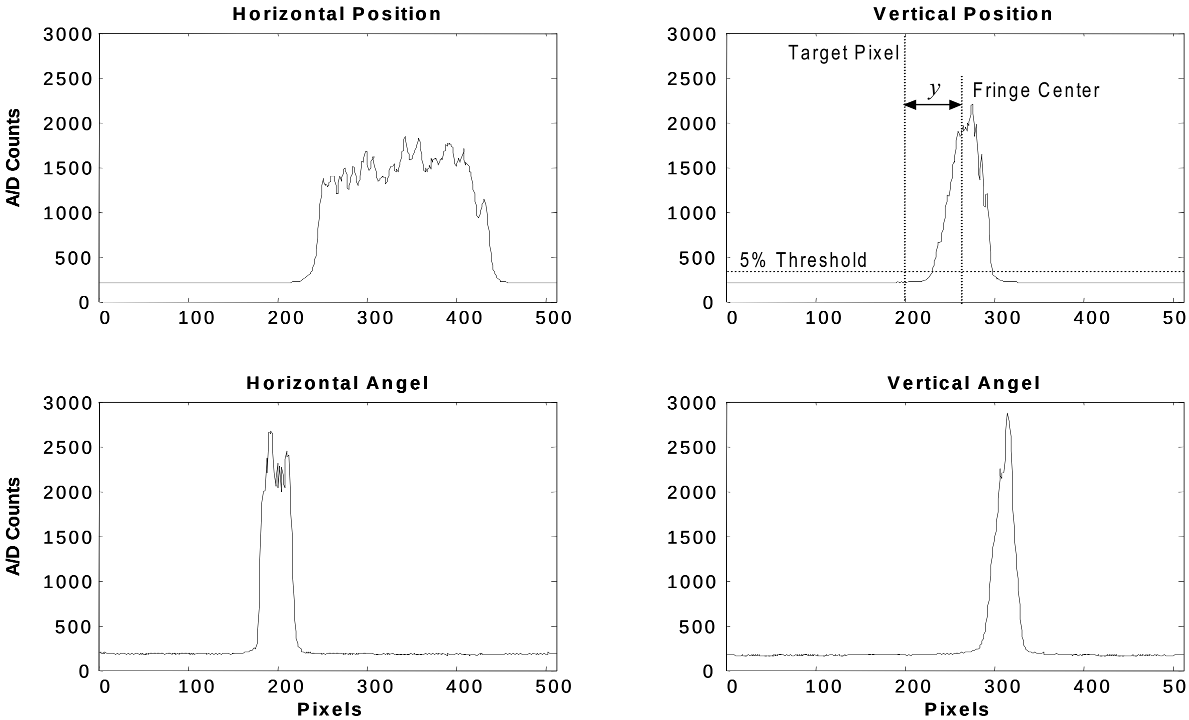


Figure 6: Typical set of PDA sensor data from Cymer BDU metrology module.

four beam fringes is coincident with these target pixel locations, there are no beam stabilization errors. In other words, the target pixel locations are defined as the set point where $x=0$, $y=0$, $\theta_x=0$, $\theta_y=0$. Therefore, the distance between the actual fringe centers and the target pixel location are the beam stabilization errors. In practice, the target pixel locations are defined during the laser-BDU-scanner instillation, and are configurable values that can be adjusted by the scanner.

Our procedure for computing the errors from the raw PDA data is broken down into two stages. In the first stage, feature finding, we identify the floor, peak, and peak pixel location for each fringe. In the second stage, evaluation, we compute the center of the fringe by locating the half-width at 5% of the peak. The algorithm begins by determining the 5% threshold between the peak and floor. A line search from the peak identifies the fractional pixel locations for the 5% threshold crossings. The fringe center is computed as the center between the rising and falling threshold crossings, and the error is finally evaluated as the distance between the fringe center and target pixel.

6. TURNING MIRROR ACTUATORS

The fundamental design of the Cymer BDU turning mirror module is shown in Figure 7. The turning mirror mounts to a fast, small stroke tip-tilt platform; the fast steering mirror. The fast steering mirror is itself mounted in a slow, large stroke tip-tilt platform. This staged actuator arrangement enables fast corrections to be made on a pulse-to-pulse timescale and large corrections to be made on wafer-to-wafer time scales. The active beam stabilization is preformed exclusively with the fast steering mirror, while slow stage is used to automatically compensate for larger drifts.

To facilitate high-bandwidth beam stabilization performance, it's important to ensure the first resonant frequency of the fast steering mirror is as high as possible. The fast steering mirrors implemented in the test BDU had a first resonance at 780Hz, as seen in the measured transfer function in Figure 8. This transfer function illustrates the dynamics from the fast steering mirror actuators to the beam pointing sensor. The pair of resonances at 780 and 1000 Hz correspond to the first vibration modes of the mirror on the fast steering motor in the tip and tilt directions.

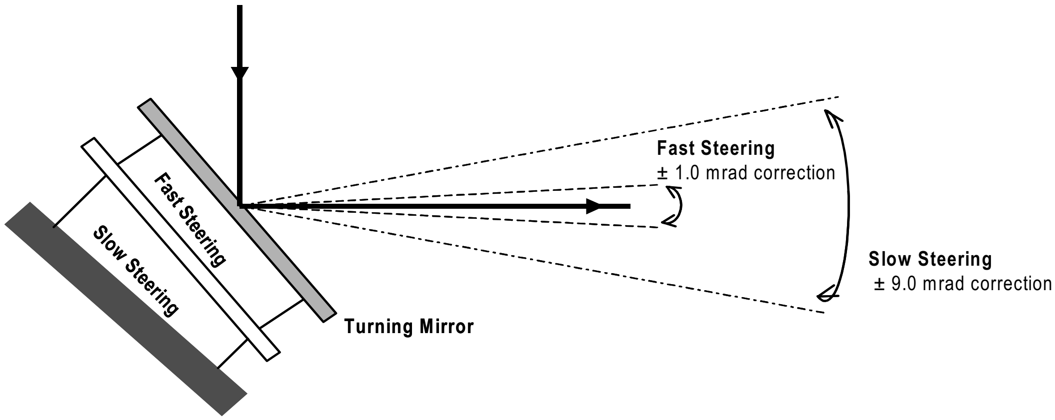


Figure 7: Illustration of turning mirror stacked actuator.

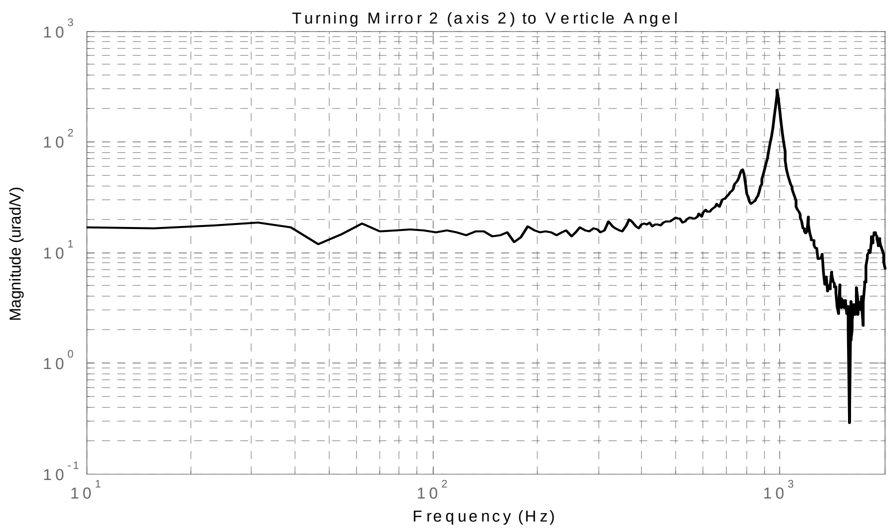


Figure 8: Measured transfer function from fast steering mirror to vertical angle at BDU exit.

7. BEAM STABILIZATION ALGORITHMS

The objective of the beam stabilization algorithm is to drive the position and pointing errors to zero. Our algorithm for doing so is illustrated in the block diagram of Figure 9. Note that we employ single axis control to regulate each beam pointing error to zero. The block diagram illustrates the computations carried out after every pulse of light. When a pulse of light passes through the BDU, the sensor metrology samples the images on the PDAs and moves the data to a digital signal processor. As detailed above, the processor computes the beam stabilization errors. These errors are then fed to independent integrators, and the integrator outputs are sent to the fast steering mirrors. Integral control is a very robust technique that applies an increasing control effort until the errors are driven to zero. The gains of the integrators, k_i, are chosen so that the beam stabilization system achieves maximal performance without exciting the lightly damped resonant modes in the turning mirrors. They are further chosen to ensure stable operation at all laser firing rates.

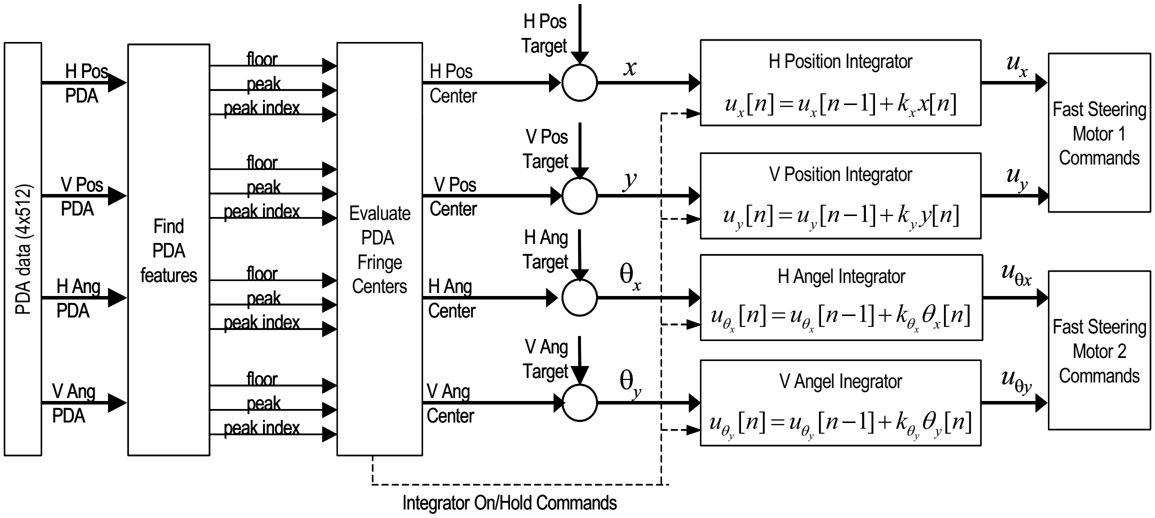


Figure 9: Detailed block diagram of the beam stabilization algorithm.

The particular wiring of integrator outputs to the fast steering mirror axes is driven by the configuration of the mirrors in the system. As illustrated in Figure 10, there is geometric coupling between the position and pointing corrections commanded by the angles of the turning mirrors. In particular, commanded angles to a given turning mirror simultaneously generate position and pointing corrections. Rather than coupling our control loops to compensate for these physics, we maintain independent control loops on each error by exploiting the dominant axes of influence. The first turning mirror has a significantly larger impact on beam position at the scanner entrance (BDU exit). Therefore, we use the first steering mirror to correct for position, and the second steering mirror to correct for pointing. Any coupling that remains is taken care of by the integrators that seek to zero all the errors. In essence, the integrators and independent loops force the turning mirrors to find the right balance of angles regardless of the coupling.

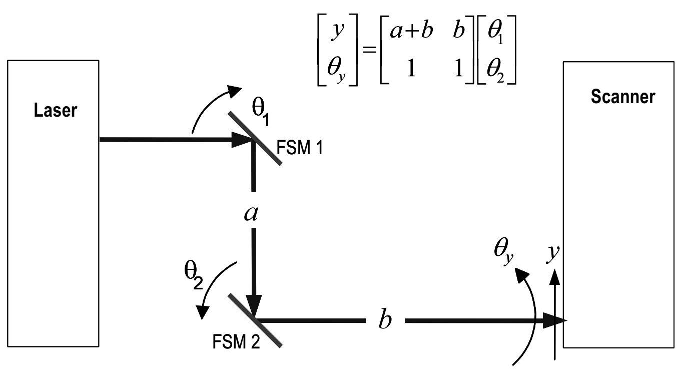


Figure 10: Illustration of geometric coupling of mirror commands to beam errors at BDU exit.

8. BEAM STABILIZATION RESULTS

The test BDU shown in Figure 3 was installed with a dual stage MOPA laser at Cymer. To illustrate the performance achieved by our beam stabilization system, we have provided a typical set of results in Figure 11. For the results shown, the laser executed a series of 70 bursts at a 4kHz rep-rate. Each burst had 400 pulses and there were 0.2s between the bursts. Each figure contains a comparison of the open loop and closed loop moving average

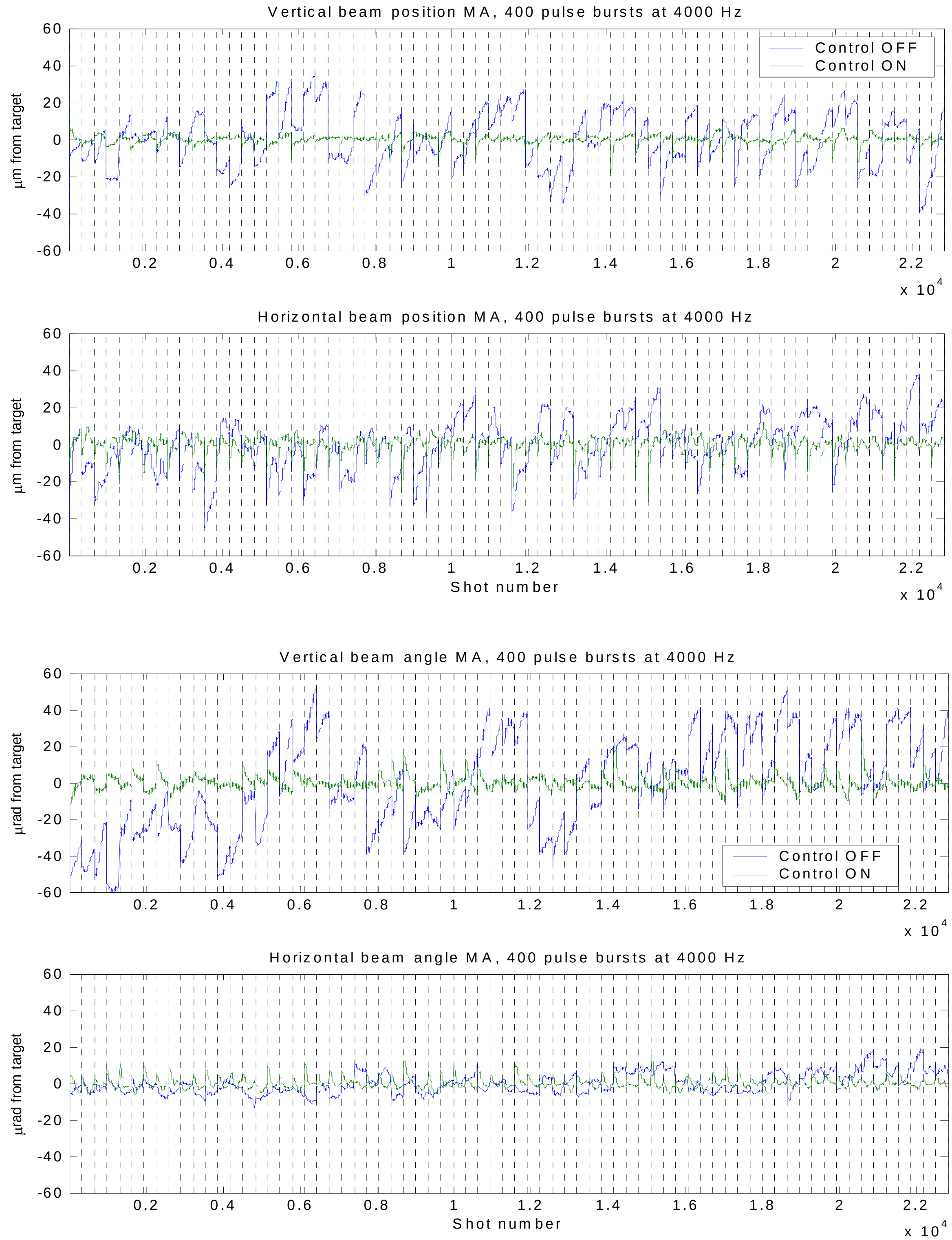


Figure 11: Beam stabilization results during simulated wafer exposure of 70 bursts, 400 pulses per burst, 4kHz rep-rate.

errors with for a 80 pulse window. Note that the horizontal scale is the shot (pulse) number, and that the vertical dashed lines separate the bursts.

Figure 12 shows a blow up of the vertical beam pointing results for a few bursts. It illustrates several key benefits of our beam stabilization system. The open loop (control off) errors measured are mainly attributed to the inherent jitter of the light source. Note two key types of errors. First, from burst to burst, there can be large jumps in the pointing angle of the beam leaving the laser. Second, there is a varying degree of pointing angle drift within a burst. The beam stabilization system is able to mitigate both of these factors, and do so while the system is exposing wafers. All in all, this system demonstrates an ability to reduce the pointing deviations by a factor of 5 (from ± 50 urad to ± 10 urad).

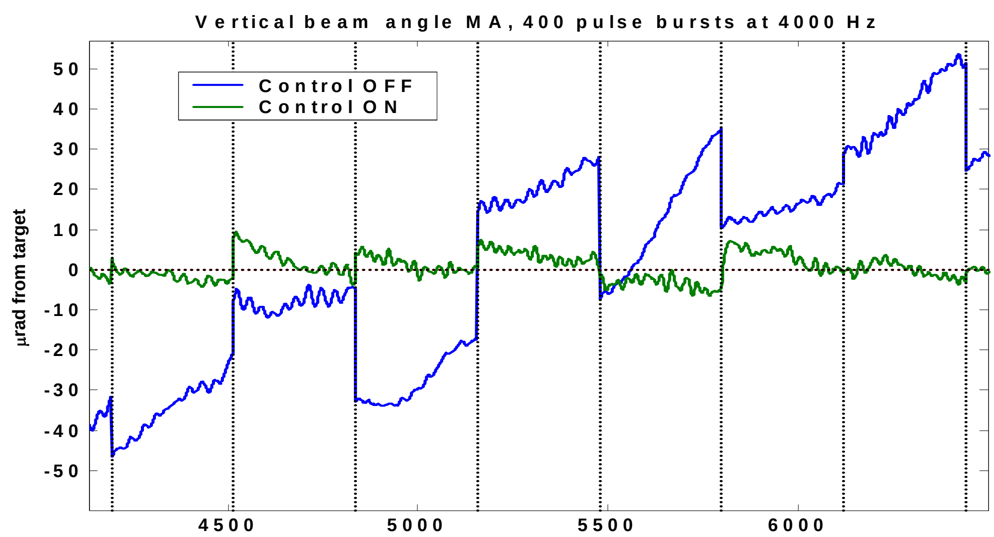


Figure 12: Zoom-in of vertical pointing results for a few bursts.

Tests were also conducted to examine the impact of floor vibrations on the beam stabilization system. Since the ambient floor vibrations were low compared to a fab, 0.08mili-G's (mG), we used a shaker to increase their intensity. Even with the added floor vibration intensity, our test BDU was relatively insensitive to floor vibrations. Figure 13 shows a comparison of beam stabilization results when we drove the floor shaker with a sinusoid at a frequency with a known mechanical resonance, 22.5Hz. The open loop (control off) data shows the inherent laser jitter characteristic with additional oscillations from the 0.3mG of floor vibration generated at 22.5Hz. In comparison, the results with the beam stabilization system on demonstrate that the beam stabilization system also rejects the pointing errors induced by the floor vibrations.

To quantify the improvement in dose stability at the wafer, we took measurements of the transmission through an aperture 1.5m down stream of the metrology module. The test setup simulated an apertured illumination system inside a scanner. Hundreds of transmission measurements were taken, where each measurement was averaged over 30 pulses. To illustrate the benefits, we plotted the number of deviations from the mean transmission with beam stabilization off and on (Figure 14). As seen in the plot, beam position and pointing control minimizes variation through the aperture. Note, that the average transmission increases by about 2.3% with control on, that is the dose on wafer is increased by 2.3%. The repeatability of the transmission also improves significantly from –5% to –3% with control on. All in all, the results demonstrate an improvement in dose stability with beam stabilization.

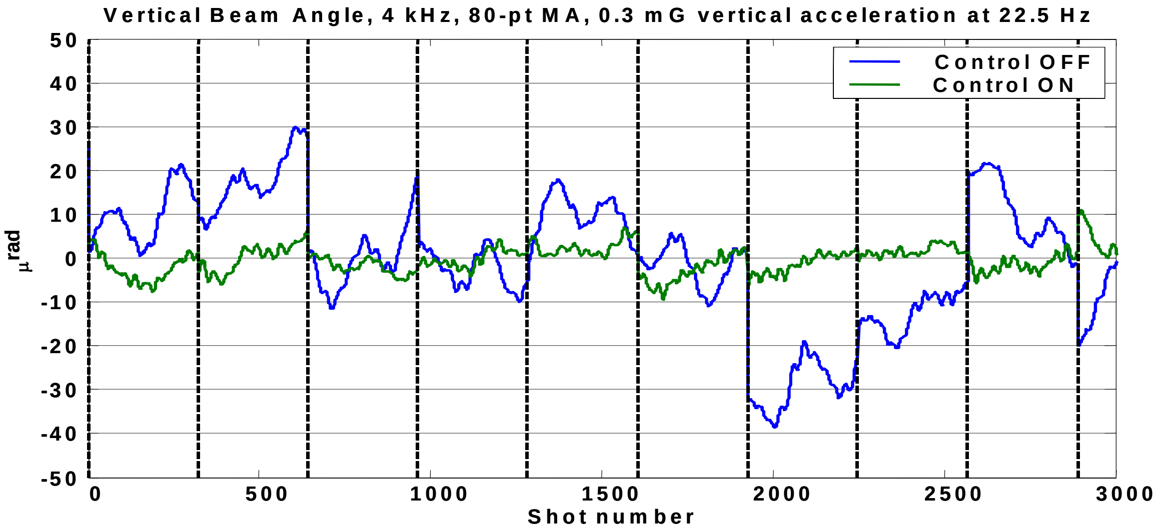


Figure 13: Beam stabilization results with amplified floor vibrations at known mechanical resonance of test BDU.

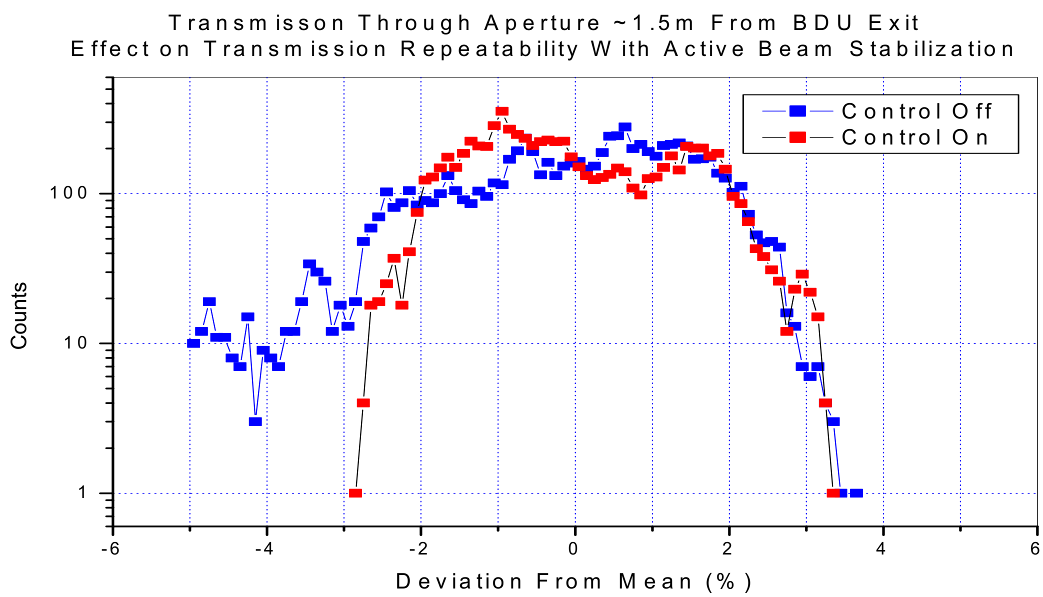


Figure 14: Impact of beam stabilization through an apertured illumination system.

9. CONCLUSIONS

Cymer has implemented a beam stabilization system that enhances stability at the scanner entrance during wafer exposure. The beam stabilization system is embodied in a modular design that will allow this performance to be realized in BDUs of various configuration in lengths up to 20m. By ensuring the beam tracks the scanner specified target on a pulse-to-pulse basis, the system can improve throughput by minimizing the time required to take the system off-line and re-align the beam delivery. Furthermore for illumination systems with beam limiting apertures,

active beam stabilization in the BDU will ensure the transmission through the aperture is higher and the repeatability of the transmission is improved.

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